Limits on the Decay-Rate Difference of Neutral B Mesons and on CP, T, and CPT Violation in $B^0\overline{B}^0$ Oscillations

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(Dated: February 7, 2008)

Using events in which one of two neutral B mesons from the decay of an $\Upsilon(4S)$ meson is fully reconstructed, we determine parameters governing decay ($\Delta\Gamma_d/\Gamma_d$), CP and T violation ($|q/p|$),

and CP and CPT violation ($\operatorname{Re} \mathsf{z}$, $\operatorname{Im} \mathsf{z}$). The results, obtained from an analysis of 88 million $\Upsilon(4S)$ decays recorded by *BABAR*, are

$$
\begin{aligned}
\operatorname{sgn}(\operatorname{Re}\lambda_{CP})\Delta\Gamma_d/\Gamma_d &= -0.008 \pm 0.037 \text{ (stat.) } \pm 0.018 \text{ (syst.) } [\,-0.084\,,\,0.068\,], \\
|q/p| &= 1.029 \pm 0.013 \text{ (stat.) } \pm 0.011 \text{ (syst.) } [\,1.001\,,\,1.057\,], \\
(\operatorname{Re}\lambda_{CP}/|\lambda_{CP}|)\operatorname{Re}\mathsf{z} &= 0.014 \pm 0.035 \text{ (stat.) } \pm 0.034 \text{ (syst.) } [\,-0.072\,,\,0.101\,], \\
\operatorname{Im}\mathsf{z} &= 0.038 \pm 0.029 \text{ (stat.) } \pm 0.025 \text{ (syst.) } [\,-0.028\,,\,0.104\,].
\end{aligned}
$$

The values inside square brackets indicate the 90% confidence-level intervals. These results are consistent with Standard Model expectations.

PACS numbers: 13.25.Hw, 12.15.Ff, 11.30.Er

In this Letter, we provide a direct limit on the total decay-rate difference $\Delta\Gamma_d$ between the B_d mass eigenstates, and set limits on CP, T, and CPT violation inherent in the mixing of neutral B mesons. In the Standard Model CPT violation is forbidden and the other effects are expected to be non-zero but small, but new physics could provide enhancements [1, 2, 3, 4]. We test these predictions by analyzing the time dependence of decays of the $\Upsilon(4S)$ resonance in which one neutral B meson ($B_{\rm rec}$) is fully reconstructed and the flavor of the other B ($B_{\rm tag}$) is identified as being either B^0 or $\overline{B}^0$. The $B_{\rm rec}$ sample is composed of flavor- and CP-eigenstate subsamples, $B_{\rm flav}$ and B_{CP}. We reconstruct the flavor eigenstates [5] $B_{\rm flav}$ $= D^{(*)-}\pi^+(\rho^+, a_1^+)$ and $J/\psi K^{*0}(\to K^+\pi^-)$ and the CP eigenstates $B_{CP} = J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, and $J/\psi K_L^0$. The flavor of the B that is not completely reconstructed is "tagged" on the basis of the charges of leptons and kaons, and other indicators [6]. The data come from 88 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector [7] at the PEP-II asymmetric-energy B Factory at SLAC.

The light and heavy B_d mass eigenstates $B_{L,H}$ are superpositions of B^0 and $\overline{B}^0$. This mixing is a consequence of transitions between B^0 and $\overline{B}^0$ through intermediate states. Flavor oscillations between B^0 and $\overline{B}^0$ occur with a frequency $\Delta m_d \equiv m_H - m_L$. A state that is initially B^0 ($\overline{B}^0$) will develop a $\overline{B}^0$ (B^0) component over time, whose amplitude is proportional to a complex factor denoted q/p (p/q) [8]. Since $|q/p| \simeq 1$ in the Standard Model, this factor is usually assumed to be a pure phase.

The most general time dependence allowed for the decays of the two neutral B mesons coming from an $\Upsilon(4S)$ is [6]

$$
\begin{aligned}
\frac{{\rm d}N}{{\rm d}\Delta t} \propto e^{-\Gamma_d|\Delta t|} &\left[\frac{|a_+|^2 + |a_-|^2}{2}\cosh\left(\frac{\Delta\Gamma_d\Delta t}{2}\right) + \right. \\
\frac{|a_+|^2 - |a_-|^2}{2}&\cos(\Delta m_d\Delta t) - \operatorname{Re}(a_+^* a_-)\sinh\left(\frac{\Delta\Gamma_d\Delta t}{2}\right) \\
&\left. + \operatorname{Im}(a_+^* a_-)\sin(\Delta m_d\Delta t) \right],\quad (1)
\end{aligned}
$$

where $\Delta t \equiv t_{\rm rec} - t_{\rm tag}$ is the signed difference in proper decay times, Γ_d is the mean decay rate of the two neutral mass eigenstates, and $\Delta\Gamma_d \equiv \Gamma_H - \Gamma_L$ is their decay-

rate difference. The values of the complex parameters $a_\pm$ differ for the various combinations of flavor and CP eigenstates into which the B mesons decay [6].

In the simplest picture, where $\Delta\Gamma_d = 0$, and CP, T, and CPT violation in mixing are neglected, if the fully reconstructed state is a flavor eigenstate the time distributions ${\rm d}N/{\rm d}\Delta t$ with perfect tagging are proportional to $e^{-\Gamma_d|\Delta t|}(1 \pm \cos(\Delta m_d\Delta t))$. In practice, the tagging is imperfect and its performance is measured directly from the data. Imperfect tagging reduces the coefficient of $\cos(\Delta m_d\Delta t)$ by a factor $1-2w$ called the dilution, where w is the probability of tagging incorrectly.

B decays to a CP eigenstate f_{CP} are conveniently parameterized by $\lambda_{CP} \equiv (q/p)(\overline{\mathcal{A}}_{CP}/\mathcal{A}_{CP})$, where $\mathcal{A}_{CP}$ ($\overline{\mathcal{A}}_{CP}$) is the amplitude for $B^0 \to f_{CP}$ ($\overline{B}^0 \to f_{CP}$). CP violation is characterized by $\lambda_{CP} \neq \eta_{CP}$ where $\eta_{CP} = \pm 1$ is the final state's CP eigenvalue. The CP violation observed in decays like $B \to J/\psi K_S^0$ [9, 10] involves interference between decays with and without net oscillation, and leads to $\operatorname{Im}\lambda_{CP} \neq 0$. Other possible sources of CP violation are $|q/p| \neq 1$ and $|\overline{\mathcal{A}}_{CP}/\mathcal{A}_{CP}| \neq 1$. We include a test of the former possibility here.

The time distributions ${\rm d}N/{\rm d}\Delta t$ for the B_{CP} samples, in the simplest picture (defined above) and with perfect tagging, are proportional to

$$
\begin{aligned}
e^{-\Gamma_d|\Delta t|} &\left[1 + |\lambda_{CP}|^2 \pm (1 - |\lambda_{CP}|^2)\cos(\Delta m_d\Delta t) \right. \\
&\left. \mp 2\operatorname{Im}\lambda_{CP}\sin(\Delta m_d\Delta t) \right]. \quad (2)
\end{aligned}
$$

In the Standard Model we have $\lambda_{CP} = -e^{-2i\beta}$ for $J/\psi K_S^0$ with the approximation $\Delta\Gamma_d = 0$, where $\beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$ is one of the angles of the triangle [11] that represents the unitarity of the quark mixing matrix V_{ij}. Since $|\lambda_{CP}| = 1$, the $\cos(\Delta m_d\Delta t)$ term is absent. Again, wrongly tagged events reduce the amplitude of the oscillatory terms.

To measure $\Delta\Gamma_d$, or CP, T, or CPT violation in mixing alone we need to find small deviations from these simple patterns. Other effects that can mimic the behavior we seek must be included in the analysis. Among these are asymmetries in the response of the detector to B^0 and $\overline{B}^0$ decays [6] and interference between dominant and suppressed decay amplitudes to flavor eigenstates, both those that are fully reconstructed and those that

contribute to tagging [6, 12].

The time dependence of the B_{CP} sample includes a $\sinh(\Delta\Gamma_d\Delta t/2)$ term that is effectively linear in $\Delta\Gamma_d$, while the flavor sample has an effective second-order sensitivity to $\Delta\Gamma_d$ through a $\cosh(\Delta\Gamma_d\Delta t/2)$ term. Untagged data are included in this analysis and improve our sensitivity to $\Delta\Gamma_d$ since the contributions of $\Delta\Gamma_d$-dependent terms do not depend on whether B_{tag} is a B^0 or $\overline{B}^0$. With our sample sizes and small measured value of $\Delta\Gamma_d$, the B_{CP} sample dominates our determination of $\Delta\Gamma_d/\Gamma_d$. While Δm_d has been well measured previously [13, 14, 15], there is only a weak limit, $|\Delta\Gamma_d|/\Gamma_d < 0.18$ at 95% CL [16], on $\Delta\Gamma_d$. A recent theoretical calculation gives $\Delta\Gamma_d/\Gamma_d = -0.003$ [1].

Violation of CP and T in mixing leads to a difference between the $B^0 \to \overline{B}^0$ and $\overline{B}^0 \to B^0$ transition rates proportional to $|q/p|^4 - 1$. Our sensitivity to $|q/p|$ comes mostly from the large flavor-eigenstate sample. Previous measurements, obtained assuming $\Delta\Gamma_d = 0$, give $|q/p| - 1 = (-0.7 \pm 6.4) \times 10^{-3}$ [17]. The Standard Model expectation is $|q/p| - 1 = (2.5 - 6.5) \times 10^{-4}$ [2].

CPT violation in mixing enters the time dependence through the complex quantity

$$\mathsf{z} \equiv \frac{\delta m_d - \frac{i}{2}\delta\Gamma_d}{\Delta m_d - \frac{i}{2}\Delta\Gamma_d} \, , \tag{3}$$

where δm_d ($\delta\Gamma_d$) is the $B^0 - \overline{B}^0$ difference of effective mass (decay rate) expectation values for the B^0 and $\overline{B}^0$ flavor eigenstates. A non-zero value of either δm_d or $\delta\Gamma_d$ is only possible if both CP and CPT are violated. The dominant contribution of $\mathrm{Im}\,\mathsf{z}$ to the time dependence is through the coefficient of $\sin(\Delta m_d\Delta t)$ for flavor eigenstates, while $\mathrm{Re}\,\mathsf{z}$ contributes primarily to the coefficients of $\cosh(\Delta\Gamma_d\Delta t/2) \approx 1$ and $\cos(\Delta m_d\Delta t)$ for CP eigenstates. The measurement of z presented here is more general than previous analyses based on B decays, which obtained $\mathrm{Im}\,\mathsf{z} = 0.040 \pm 0.032 \pm 0.012$ [18], and $\mathrm{Re}\,\mathsf{z} = 0.00 \pm 0.12 \pm 0.02$, $\mathrm{Im}\,\mathsf{z} = -0.03 \pm 0.01 \pm 0.03$ [14], and complements earlier limits on the $K^0 - \overline{K}^0$ mass difference $\delta m_K/m_K < 10^{-18}$ [8].

Interference effects between the amplitudes for dominant decays of flavor eigenstates (e.g., $B^0 \to D^-\pi^+$) and for doubly-CKM-suppressed (DCS) decays (e.g., $\overline{B}^0 \to D^-\pi^+$) are analogous to the interference familiar in decays to CP eigenstates [12]. They thus affect, in particular, the $\sin(\Delta m_d\Delta t)$ terms and have the potential to obscure a similar contribution from $\mathrm{Im}\,\mathsf{z}$. The size of the DCS interference relative to the dominant B^0 decay is governed by λ_{Bf} and λ_{Bt}, for B_{flav} and B_{tag} states, respectively. These parameters are defined analogously to λ_{CP}, and we expect $|\lambda_{Bf,Bt}| \approx |q/p||V_{\text{ub}}V_{\text{cd}}^*/V_{\text{cb}}^*V_{\text{ud}}| \simeq 0.02|q/p|$ [6]. There are similar interference contributions from DCS amplitudes for $\overline{B}^0$ decays, governed by $\lambda_{\overline{B}f}$ and $\lambda_{\overline{B}t}$. We write $\overline{\lambda}_{\overline{B}f,\overline{B}t} = 1/\lambda_{\overline{B}f,\overline{B}t}$ so $|\overline{\lambda}_{\overline{B}f,\overline{B}t}| \approx 0.02|p/q|$. The B_{flav} and B_{tag} samples are ensembles of final states that each contribute to the expected decay-rate

distributions with different amplitudes. We find that, working to first order in the small quantities $|\lambda_{Bf,Bt}|$, $|\overline{\lambda}_{\overline{B}f,\overline{B}t}|$, $|\mathsf{z}|$, and $|q/p| - 1$, the cumulative effect of each ensemble does not modify the expected decay-rate distributions, once $\lambda_{Bf,Bt}$ and $\overline{\lambda}_{\overline{B}f,\overline{B}t}$ are reinterpreted as effective parameters.

We combine all the data for the CP eigenstates, taking into account the CP eigenvalue of the final state. We assume $|\overline{\mathcal{A}}_{CP}/\mathcal{A}_{CP}| = 1$ (but vary this ratio as a systematic study) as expected theoretically at the 10^{-3} level [19] and as supported by the average of B-Factory measurements of states of charmonium and K_S^0 or K_L^0, for which it was found $|\overline{\mathcal{A}}_{CP}/\mathcal{A}_{CP}| = 0.949 \pm 0.045$ [9, 10], when $\Delta\Gamma_d = 0$ and $|q/p| = 1$ are assumed.

The time interval Δt between the two B decays is calculated from the measured separation Δz between the decay vertices of B_{rec} and B_{tag} along the collision axis [9]. We determine the position of the B_{rec} vertex from its charged tracks. The B_{tag} decay vertex is determined by fitting to a common vertex tracks not belonging to the B_{rec} candidate, employing constraints from the beam spot location and the B_{rec} momentum [9]. The r.m.s. Δt resolution for 99.7% of the events used is 1.0 ps, to be compared with $\langle|\Delta t|\rangle \simeq 1.5$ ps.

Resolution effects for signal events are modeled by convolving the idealized decay rate with a sum of three Gaussian distributions, two of whose widths and biases are scaled with each event's estimated Δt uncertainty $\sigma_{\Delta t}$.

We use four mutually-exclusive categories to assign tags, based on kinematic, particle type, and charge information [9]. There are separate reconstruction efficiencies and mistag probabilities for B^0 and $\overline{B}^0$ tags, to accommodate differences in detector response to B^0 and $\overline{B}^0$ decays. In addition, we introduce a linear dependence of the mistag probability on $\sigma_{\Delta t}$, except for events tagged with a high-momentum lepton.

Backgrounds are primarily due to misreconstructed B_{rec} candidates and are studied in data using mass or energy sidebands. Events are assigned signal and background probabilities based on their proximity to the signal peak. We model backgrounds with empirical Δt distributions that can accommodate contributions from decays with a range of lifetimes.

The parameters of primary interest in this analysis are $\mathrm{sgn}(\mathrm{Re}\,\lambda_{CP})\Delta\Gamma_d/\Gamma_d$, $|q/p|$, $(\mathrm{Re}\,\lambda_{CP}/|\lambda_{CP}|)\,\mathrm{Re}\,\mathsf{z}$, and $\mathrm{Im}\,\mathsf{z}$. We cannot determine $\Delta\Gamma_d/\Gamma_d$ and $\mathrm{Re}\,\mathsf{z}$ directly because both occur multiplied by $\mathrm{Re}\,\lambda_{CP}$ in their dominant contributions to the decay rate. They are thus subject to a sign ambiguity, which can be resolved by relying on additional information from the unitarity triangle. The average lifetime $\tau_{B^0} \equiv 1/\Gamma_d$ is fixed at 1.542 ps [8]. The parameters Δm_d and $\mathrm{Im}\,\lambda_{CP}/|\lambda_{CP}|$ are determined together with the main parameters as cross checks against earlier measurements [9, 13]. The terms proportional to the real parts of the effective DCS parameters $\lambda_{Bf,Bt}$ and $\overline{\lambda}_{\overline{B}f,\overline{B}t}$, are small and therefore neglected in the nomi-

TABLE I: Fit results allowing (z free) or not allowing (z = 0) CPT violation in $B^0\overline{B}^0$ oscillations.

Parameter	z Free	z = 0
$\mathrm{sgn}(\mathrm{Re}\,\lambda_{CP})\Delta\Gamma_d/\Gamma_d$	-0.008 ± 0.037	-0.009 ± 0.037
$|q/p|$	1.029 ± 0.013	1.029 ± 0.013
$(\mathrm{Re}\,\lambda_{CP}/|\lambda_{CP}|)\,\mathrm{Re}\,\mathsf{z}$	0.014 ± 0.035	—
$\mathrm{Im}\,\mathsf{z}$	0.038 ± 0.029	—

TABLE II: Summary of systematic uncertainties (z free).

Source	$\mathrm{sgn}(\mathrm{Re}\,\lambda_{CP})$ $\times \Delta\Gamma_d/\Gamma_d$	$|q/p|$	$\mathrm{Re}\,\lambda_{CP}/|\lambda_{CP}|$ $\times \mathrm{Re}\,\mathsf{z}$	$\mathrm{Im}\,\mathsf{z}$
Analysis Method	0.006	0.007	0.005	0.016
Δt Resolution	0.013	0.003	0.008	0.016
Signal Properties	0.010	0.008	0.033	0.009
BG Properties	0.005	0.003	0.007	0.004
Total	0.018	0.011	0.034	0.025

nal fit model, while the imaginary parts and magnitudes of these effective parameters are treated as independent variables. For all sets of nonleptonic flavor eigenstates analyzed, the magnitude of each $|\lambda|$ is fixed to 0.02 (up to a factor $|q/p|$ or $|p/q|$) but $\mathrm{Im}\,\lambda/|\lambda|$ is left unconstrained. The decay model uses 26 more parameters to model the effects of experimental Δt resolution (10), $B^0/\overline{B}^0$ tagging capability (11), and reconstruction and tagging efficiencies (5). An additional 22 parameters model the levels and Δt dependence of backgrounds. A total of 58 free parameters are determined with a simultaneous unbinned maximum-likelihood fit to the Δt distributions of CP and flavor-eigenstate samples [6].

Table I summarizes the results of fits allowing (z free) or not allowing (z = 0) CPT violation in $B^0\overline{B}^0$ oscillations. The largest statistical correlations involving the parameters of interest are between $|q/p|$ and parameters modeling $B^0\overline{B}^0$ asymmetries in reconstruction efficiency and mistag probabilities, and between $\mathrm{Im}\,\mathsf{z}$ and the DCS contributions to B_{tag} decay amplitudes. The fitted values of Δm_d and $\mathrm{Im}\,\lambda_{CP}/|\lambda_{CP}|$ are consistent with recent B-Factory measurements [9, 10, 13, 15]. When z is fixed, the value of $\mathrm{Im}\,\lambda_{CP}/|\lambda_{CP}|$ decreases by 0.011, equal to 15% of the statistical uncertainty on $\mathrm{Im}\,\lambda_{CP}/|\lambda_{CP}|$ which is consistent with the correlations observed in the fit with z free, while the value of and uncertainty in Δm_d are unchanged. No statistically significant B^0-$\overline{B}^0$ differences in reconstruction and tagging efficiencies are observed.

We have used data and Monte Carlo samples to validate our analysis technique. Tests with large, parameterized Monte Carlo samples demonstrate that the observed statistical uncertainties and correlations are consistent with expectations. Analyses of Monte Carlo samples generated with a detailed detector simulation verify that the analysis procedure is unbiased. Fits to data subsamples selected by tagging category, running period, and B_{rec} decay mode give consistent results. Changes to the algorithms used to estimate Δt and $\sigma_{\Delta t}$ or to their allowed ranges also have no statistically significant effect. Fits to samples of charged B decays, in which no oscillations are present, give the expected results.

We identify four general sources of systematic uncertainty with the contributions shown in Table II for the fit in which z is free [6]. The first is possible bias in the event selection and fit method: we see no evidence of such bias when analyzing Monte Carlo samples and

assign the statistical uncertainty of these checks as a systematic uncertainty on the final results. The second is the Δt measurement. The choice of parameterization of the resolution function dominates this uncertainty, but assumptions about the beam spot and detector alignment contribute as well. Assumptions about the properties of signal $\Upsilon(4S) \to B_{\mathrm{rec}}B_{\mathrm{tag}}$ decays include the values of the lifetime, $|\overline{\mathcal{A}}_{CP}/\mathcal{A}_{CP}|$, and DCS parameters, and are the third source of systematic uncertainty. Uncertainties in the size and Δt distributions of background events (BG) incorrectly identified as $\Upsilon(4S) \to B_{\mathrm{rec}}B_{\mathrm{tag}}$ make small contributions to the systematic uncertainties.

Different sources dominate the systematic uncertainty for each parameter. Most systematic uncertainties are determined with data and will decrease with additional statistics. The largest single source of uncertainty is the contribution of the DCS parameters to $(\mathrm{Re}\,\lambda_{CP}/|\lambda_{CP}|)\,\mathrm{Re}\,\mathsf{z}$ and it is estimated by varying the DCS phase parameters over their full allowed range, and $|\overline{\mathcal{A}}_{Bf}/\mathcal{A}_{Bf}|$ and $|\mathcal{A}_{\overline{B}f}/\overline{\mathcal{A}}_{\overline{B}f}|$ over the range 0–0.04. Systematic uncertainties on $\mathrm{sgn}(\mathrm{Re}\,\lambda_{CP})\Delta\Gamma_d/\Gamma_d$ and $|q/p|$ for the analysis assuming z = 0 were evaluated similarly as ± 0.018 and ± 0.011, respectively.

Using the world-average value of Δm_d [8], we derive the value $\mathrm{sgn}(\mathrm{Re}\,\lambda_{CP})\Delta\Gamma_d/\Delta m_d = -0.011 \pm 0.049(\mathrm{stat.}) \pm 0.024(\mathrm{syst.})$, corresponding to the range [-0.112,0.091] at the 90% confidence level, from the fit results with z free. The limit on CP and T violation in oscillations is independent of and consistent with our previous measurement based on an analysis of inclusive dilepton events [20]. Using Eq. (3) and taking the world-average B_d mass [8], we derive $|\delta m_d|/m_{B_d} < 1.0 \times 10^{-14}$ and $-0.156 < \delta\Gamma_d/\Gamma_d < 0.042$ at the 90% confidence level. Figure 1 shows the results of the fit with z free in the $(|q/p|-1, |\mathsf{z}|)$ plane, compared to the previous BABAR measurement of $|q/p|$, and to Standard Model expectations.

Conventional analyses of oscillations and CP violation in the B_d system neglect possible contributions from several sources that are expected to be small in the Standard Model. This analysis includes these effects and finds results consistent with Standard Model expectations. While the Standard Model predictions for $\Delta\Gamma_d$, $|q/p|$, and z are well below our current sensitivity, higher-precision measurements may still bring surprises.
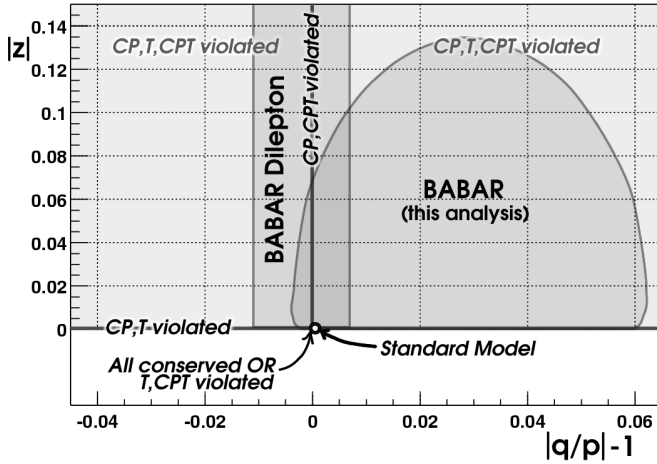
FIG. 1: Favored regions at 68% confidence level in the ($|q/p|-1$, $|z|$) plane determined by this analysis and by the *BABAR* measurement of the dilepton asymmetry [20]. Labels reflect the requirements that both *CP* and *T* be violated if $|q/p| \neq 1$ and that both *CP* and *CPT* be violated if $|z| \neq 0$. The dilepton measurement constrains $|q/p|$ without assumptions on the value of $|z|$. The Standard Model expectation of $|q/p|-1 = (2.5 - 6.5) \times 10^{-4}$ is obtained from Ref. [2].

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